# Multi-frequency evaporative cooling to BEC in a high magnetic field.

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## Abstract

We demonstrate a way to circumvent the interruption of evaporative cooling observed at high bias field for $^{87}$Rb atoms trapped in the $(F = 2, m = +2)$ ground state. Our scheme uses a 3-frequencies-RF-knife achieved by mixing two RF frequencies. This compensates part of the non linearity of the Zeeman effect, allowing us to achieve BEC where standard 1-frequency-RF-knife evaporation method did not work. We are able to get efficient evaporative cooling, provided that the residual detuning between the transition and the RF frequencies is smaller than the power broadening of the RF transitions at the end of the evaporation ramp.

Forced evaporative cooling of atoms [1,2] in a magnetic trap is at the moment the only known way to achieve Bose-Einstein condensation [3–5]. Particles with energy significantly larger than the average thermal energy are removed from the trap and the remaining ones thermalize to a lower temperature by elastic collisions. For that, a radiofrequency (RF) magnetic field is used to induce a multi-photon transition from a trapping state to a non-trapping state via all intermediate Zeeman sublevels. Atoms moving in the trap with sufficient energy can reach the resonance point (RF knife) and exit the trap. If the RF-frequency is decreased slowly enough, and no other process is hampering the forced-evaporation, the increase of the phase space density obtained by this method eventually leads to Bose-Einstein condensation.

In a previous publication [6], we reported that RF forced evaporative cooling of $^{87}$Rb atoms in the $(F = 2, m = +2)$ ground state in a magnetic trap with a high bias field is hindered and eventually interrupted. Our interpretation of this phenomenon is based on the non-linear terms of the Zeeman effect that lift the degeneracy of transition frequencies between adjacent Zeeman sublevels. This interpretation is supported by numerical calculations [7]. Interrupted evaporative cooling in a large magnetic field is a serious problem in several situations, interesting for practical reasons – like the use of permanent magnets [8] or of an iron core electromagnet as the one described in [9]. High magnetic field evaporation is also important in connection with Feshbach resonances [10–13]. In this paper, we demonstrate that it is possible to achieve efficient evaporative cooling in a high magnetic field, by use of a multi-frequency RF knife allowing a multi-photon transition to take place across non equidistant levels. We show that, for our range of magnetic fields, it is possible to use a simple experimental scheme where the three required frequencies are obtained by RF frequency mixing yielding a carrier and two sidebands.

We focus in this paper on $^{87}$Rb in the $F = 2$ manifold of the electronic ground state. Atoms are initially trapped in the $m = +2$ state. Our high bias field magnetic trap follows the Ioffe-Pritchard scheme. To the second order in position (see eq. 1 in [6]), the magnetic field modulus $B$ has a 3D quadratic dependence allowing trapping, plus a bias field $B_0$ between 50 and 200 Gauss. This is much larger than in most other experiments where $B_0$ can be independently adjusted, and is set typically at 1 Gauss [14]. In a large magnetic field, the non linear terms are not negligible in the Zeeman shifts given by the Breit-Rabi formula

$$E_m(B) = m g_{\rm I} \mu_{\rm n} B + \frac{\hbar\omega_{\rm HF}}{2}\left(\sqrt{1 + m\xi + \xi^2} - 1\right) \quad (1)$$

with

$$\xi = \frac{(g_{\rm S}\mu_{\rm B} + g_{\rm I}\mu_{\rm n})B}{\hbar\omega_{\rm HF}}.$$

Here $g_{\rm S} \simeq 2.002$ and $g_{\rm I} \simeq 1$ are respectively the Landé factor for the electron and the nucleus, $\mu_B$ and $\mu_n$ are the Bohr magneton and the nucleus magneton, and $\omega_{\rm HF}$ ($2\pi \times 6834.7$ MHz) is the hyperfine splitting.

Compared to the low magnetic field case [1,2], the evaporation process changes drastically. At a given magnetic field, the spacings between adjacent sublevels ($|\Delta m| = 1$) are not equal and the direct multi-photon transition from trapping to non-trapping states becomes negligible. Evaporation of hot atoms can only happen via a sequence of one-photon transitions of limited efficiency (see fig. 8 in [15]) separated in space. This results in long lasting atoms in the $m = +1$ and $m = 0$ states [16] responsible for hindered evaporative cooling. Moreover, transitions to non-trapping states are suppressed at the end of the evaporation ramp, leading to an interruption of cooling before BEC is reached.

To overcome these limitations, 3 distinct RF fields can be used to induce a direct three photon transition from the $m = +2$ trapping state to the $m = -1$ non trapping state. At a magnetic field $B$, the three RF frequencies must match the transition frequencies defined by:

$$\begin{aligned} \omega_0 - \delta\omega_0' &= (E_2 - E_1)/\hbar \\ \omega_0 &= (E_1 - E_0)/\hbar \\ \omega_0 + \delta\omega_0 &= (E_0 - E_{-1})/\hbar \end{aligned} \quad (2)$$

with $E_m$ taken from eq.(1).

Fig. 1 represents all possible transitions induced by these three RF frequencies in the magnetic trap. At position $K$, each RF field is resonant with a given transition : the smallest RF frequency with the $(m = +2) \rightarrow (m = +1)$ transition, the intermediate frequency with the $(m = +1) \rightarrow (m = 0)$ transition, and the largest frequency with the $(m = 0) \rightarrow (m = -1)$ transition; this is where the 3-photon transition occurs. Because of the ordering of the three RF frequencies, the points where one-photon transitions can be induced from $m = +2$ to $m = +1$ by the two larger frequencies are located beyond $K$ (the multi-photon knife). Consequently, during the evaporation, hot atoms will first encounter the three photon knife and be expelled from the trap, provided that the RF power is large enough to enable efficient multi-photon adiabatic passage to the non-trapping state $m = -1$.

The discussion above shows that in principle, the multi-frequency evaporation requires a synchronized non trivial sweep of three different frequencies in the 100 MHz range, with an accuracy of a few kHz (see below). We have rather implemented a simplified scheme where the three frequencies are obtained by mixing a carrier at frequency $\omega_{\mathrm{RF}}$ with a smaller frequency $\delta\omega_{\mathrm{RF}}$. We then obtain three equally spaced radiofrequency fields : $\omega_{\mathrm{RF}} - \delta\omega_{\mathrm{RF}}$, $\omega_{\mathrm{RF}}$, $\omega_{\mathrm{RF}} + \delta\omega_{\mathrm{RF}}$, of approximately the same power (as checked with a spectrum analyzer). Since in general $\delta\omega_0$ and $\delta\omega_0'$ are slightly different, the RF frequencies will not exactly match the transition frequencies of eq.(2). Nonetheless, they compensate the second order (quadratic) term of the Zeeman shift, and should work under certain condition discussed hereafter.

At the position where the three-photon transition is resonant, the carrier frequency $\omega_{\mathrm{RF}}$ will verify

$$3\omega_0 + \delta\omega_0 - \delta\omega_0' = 3\omega_{\mathrm{RF}} \tag{3}$$

but there will be a residual detuning for each one photon step of the multi-photon transition. For example, the optimum $\delta\omega_{\mathrm{RF}}$ that maximizes the multi-photon transition probability will be

$$\delta\omega_{\mathrm{RF}} = \frac{\delta\omega_0 + \delta\omega_0'}{2} \tag{4}$$

and the residual detunings for each intermediate steps of the three photons transition are both equal to

$$\Delta = \frac{\delta\omega_0 - \delta\omega_0'}{6}. \tag{5}$$

If the Rabi frequency $\Omega_{\mathrm{RF}}$ associated with each one photon transition is significantly larger than the residual detuning $\Delta$, the multi-photon transition is quasi resonant in the intermediate levels, leading to an effective Rabi frequency $\Omega_{\mathrm{eff}} \propto \Omega_{\mathrm{RF}}$. If on the other hand $\Omega_{\mathrm{RF}}$ is smaller than $\Delta$, the effective Rabi frequency is

$$\Omega_{\mathrm{eff}} \propto \frac{\Omega_{\mathrm{RF}}^3}{\Delta^2} \tag{6}$$

and the multi-photon transition is inefficient for evaporation ; we are then in the scheme of hindered and interrupted evaporation. We therefore expect that our scheme will be efficient for small enough magnetic field when the residual detuning $\Delta$ is smaller than the one-photon Rabi frequency $\Omega_{\mathrm{RF}}$.

Table I gives the values of the Zeeman shifts and the difference $\delta\omega_0 - \delta\omega_0'$ for various magnetic fields. For the RF power used in this scheme, the one photon Rabi frequency $\Omega_{\mathrm{RF}}$ is of the order of 10 kHz, and the discussion above shows that our simplified 3-knives evaporation scheme should work for magnetic fields significantly less than a hundred Gauss. This is what we observe: it is impossible to achieve BEC in bias fields of 207 Gauss and 110 Gauss, but BEC is obtained in a trap with a bias field of 56 Gauss, by using an appropriate sideband splitting $\delta\omega_{\mathrm{RF}}$ kept constant while ramping down the carrier frequency $\omega_{\mathrm{RF}}$.

Figure 2 shows the effect of the sideband splitting $\delta\omega_{\mathrm{RF}}$ at a bias field value of 56 Gauss. We have plotted the number of condensed atoms as a function of $\delta\omega_{\mathrm{RF}}$, all other parameters being kept unchanged. This is a good indication of the efficiency of the evaporation. The curve shows a maximum at $\delta\omega_{\mathrm{RF}} = 2\pi \times 0.45$ MHz. This value verifies equation (4) for a magnetic field of 56.6 Gauss. This magnetic field corresponds to the position of the RF knife at the end of the ramp. We conclude that frequency matching is mostly important in the last part of the radiofrequency ramp. The width of the curve is about 10 kHz (HWHM) which corresponds to power broadening [17].

Table II report experimental data, showing quantitatively the efficiency of our simplified 3-knives scheme, without which BEC could not be obtained at 56 Gauss. It is interesting to note that even when the magnetic field is too large to allow our simplified 3-knives scheme to reach BEC, it is nevertheless more efficient than a simple 1-frequency knife, since it allows us to reach a significantly lower temperature. It is also remarkable that an efficient evaporation was obtained at a bias field of 56 Gauss, since the beginning of the evaporation takes place in a larger magnetic field (of the order of 200 Gauss) where the condition (4) does not hold, and the detuning of the intermediate one photon transitions is much larger than the Rabi frequency $\Omega_{\mathrm{RF}}$. Although it has not been much noticed, a similar situation is encountered in most BEC experiments (using 1-frequency knife evaporation) : the non linear Zeeman effect at the beginning of the evaporation is often much larger than the Rabi frequency, and the evaporation hampering described in [6] is certainly happening then. The success of these experiments as well as of our 3-frequencies scheme shows that whether the evaporation is hindered or not only matters at the end of the evaporation ramp. To understand qualitatively this observation, we can note that the heating induced by the atoms populating the intermediate levels should not vary drastically with the temperature of the cooled cloud. At the beginning of the evaporation, i.e. "high" temperatures, the relative heating stays negligible [18]. Close to the end, i.e. "low" temperature, when heating should give rise to hampered evaporative cooling, evaporation is fully efficient and the intermediate levels are completely depleted. This could explain the success of BEC experiments. To verify these assumptions, more theoretical work, for instance in the spirit of [7], is needed.

In conclusion, we have demonstrated a scheme to circumvent the hindrance and interruption of evaporative cooling in the presence of non linear Zeeman effect. We implement a 3-frequency evaporative knife by a modulation of the RF field, yielding two sidebands. This scheme allows us to obtain BEC of $^{87}$Rb atoms in the $(F = 2, m = +2)$ ground state in a bias field of 56 Gauss, where the standard 1-frequency RF evaporation scheme fails. Our observations also support the physical ideas presented in our previous work to explain the hindrance and interruption of evaporative cooling in a high magnetic field, as well as the qualitative discussions of this paper.

The success of this simplified scheme and the complementary observations reported in this paper, indicate that a more sophisticated multi-frequency evaporation scheme should work at larger bias field, provided that the resonance in the intermediate steps of the multi-photon transition is achieved within the Rabi frequency of the one photon transitions, at the end of the evaporative ramp.

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## FIGURES

FIG. 1. Implementation of 3-RF-knife to evaporate in a high magnetic field. All possible transitions are represented. Evaporation happens at $K$ via a 3-photon-transition resonant in the intermediate states.

FIG. 2. Bose Einstein condensation with 3 RF knives : number of atoms in the condensate versus the sideband frequency $\delta\omega_{\mathrm{RF}}$. The width of the curve is of the order of the Rabi frequency of a one-photon RF transition.

## TABLES

| $B$ (Gauss) | 56 | 110 | 207 |
|---|---|---|---|
| $\omega_0 - \delta\omega_0'$ ($2\pi\times$ MHz) | 39.058-0.434 | 76.255-1.621 | 141.800-5.398 |
| $\omega_0$ ($2\pi\times$ MHz) | 39.058 | 76.255 | 141.800 |
| $\omega_0 + \delta\omega_0$ ($2\pi\times$ MHz) | 39.058+0.449 | 76.255+1.732 | 141.800+6.096 |
| $\delta\omega_0 - \delta\omega_0'$ ($2\pi\times$ kHz) | 15 | 111 | 698 |

TABLE I. Zeeman effect for different magnetic fields, calculated from the Breit-Rabi formula.

| $B_0$ (Gauss) | 56 | 110 | 207 |
|---|---|---|---|
| $T_{1\text{knife}}(\mu\text{K})$ | 10 | 50 | 100 |
| $T_{3\text{knives}}$ ($\mu$K) | 0.1 | 0.5 | 15 |
| $n\lambda^3_{3\text{knives}}$ | $> 2.612$ | 0.1 | $10^{-3}$ |

TABLE II. Experimental results : lowest temperature achievable with and without side band activated, and highest phase space density achieved for different bias field. At a bias field of 56 Gauss, our 3-frequency scheme yields BEC, while a single frequency scheme fails because of interrupted evaporative cooling.

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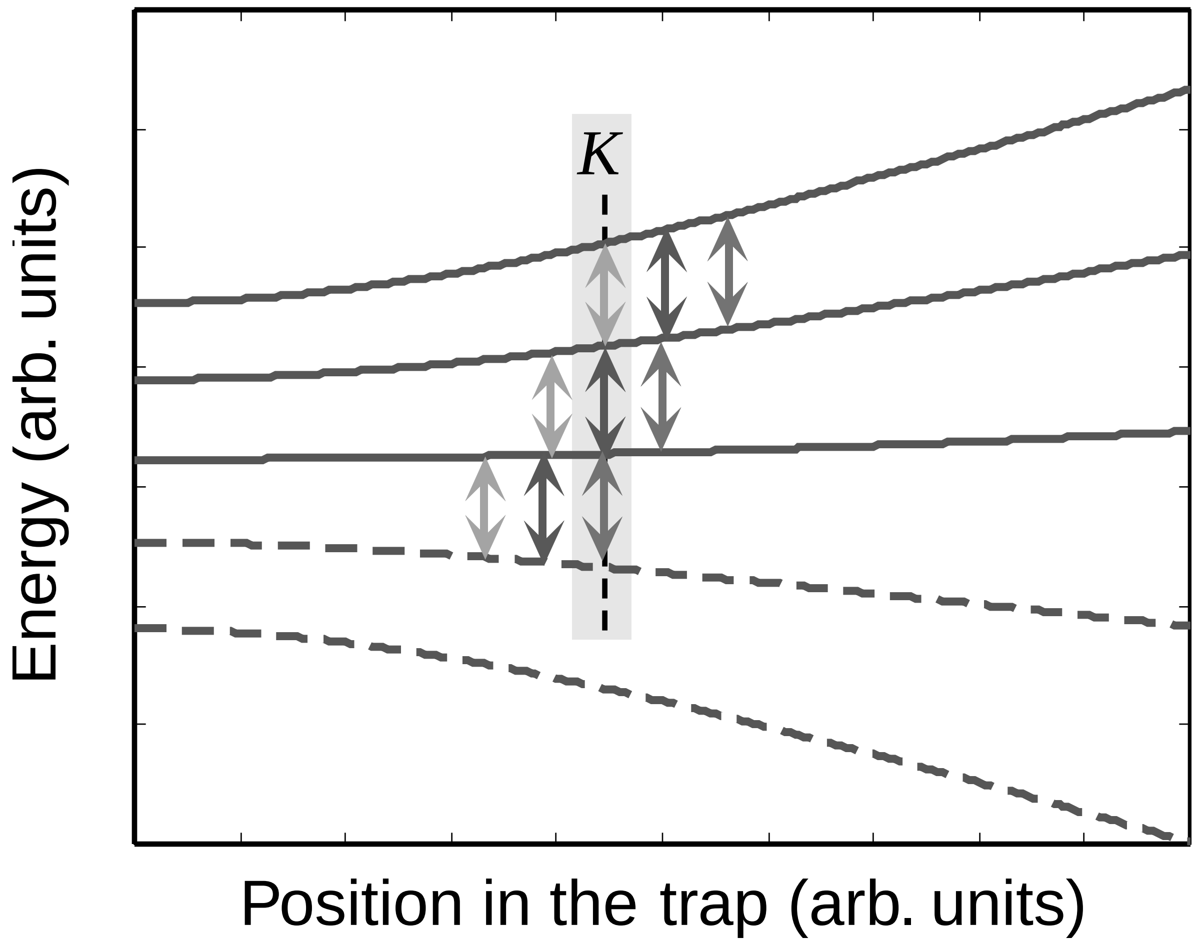
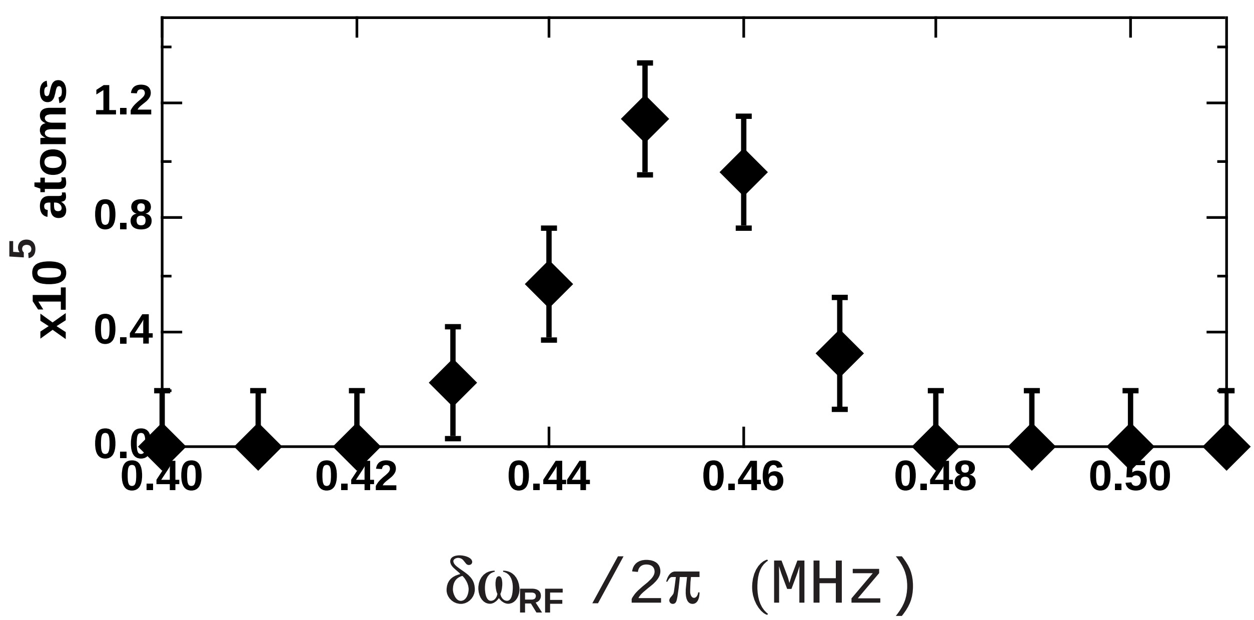
[16] The $m = 0$ state is a trapping state in this manifold because of the non linearity of the Zeeman effect.

[17] This conclusion was corroborated by a calculation of the energies of the dressed states for a given set $\{\Omega_{\mathrm{RF}}, \omega_{\mathrm{RF}}, \delta\omega_{\mathrm{RF}}\}$. From the calculated energy splitting $C \simeq \Omega_{\mathrm{eff}}$ at the $(m = +2, m = -1)$ level crossing, we used the two-levels Landau Zener probability that the atoms will follow an adiabatic transition. We verified that for small Rabi frequencies (i.e. small evaporation efficiency), as in our experiment, this 3-photon transition is the most probable transition at any sideband detuning $\delta\omega_{\mathrm{RF}}$. This numerical calculation can be used to fit the experimental data. We can estimate the one-photon Rabi frequency $\Omega_{\mathrm{RF}} = 2\pi \times 8 \pm 4$ kHz.

[18] Except maybe for the case of destructive energy releasing collisions as in $^{23}Na$. See P.S. Julienne, F.H. Mies, E. Tiesinga, and C.J. Williams, Phys. Rev. Lett, **78**, 1880 (1997)


K
Energy (arb. units)
Position in the trap (arb. units)



x10^5 atoms
1.2
0.8
0.4
0.0
0.40
0.42
0.44
0.46
0.48
0.50
δω_RF /2π (MHz)